Evaluation of Greenhouse Gas Emissions Associated with Recycled-Content Products

California Purchasing Guidelines for Plastic Products

CalRecycle

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Contractor's Report

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Scope and Methodology

This document provides estimates for the energy and greenhouse gas (GHG) emission savings that can be achieved by purchasing plastic products with recycled polymer content. It covers the following products:

Table 1: Products covered in the Recycled Content Guidelines Document.

Material	Resin Identification Code	Forming Operation
Polyethylene Terephthalate (PET)	1	Thermoforming
Polyethylene Terephthalate (PET)	1	Injection Stretch Blow Molding
High Density Polyethylene (HDPE)	2	Blow molding
Polypropylene (PP)	5	Injection Molding
General Purpose Polystyrene (GPPS)	6	Injection Molding

The energy and greenhouse gas calculations are based on process-based life-cycle assessment (LCA), which uses a model of the sequence of processes involved in a product's life-cycle to estimate environmental impacts. The life-cycle impact is calculated as the sum of the impacts of all the individual processes. The methodology for process-based LCA is described in ISO 14040 and ISO 14044.

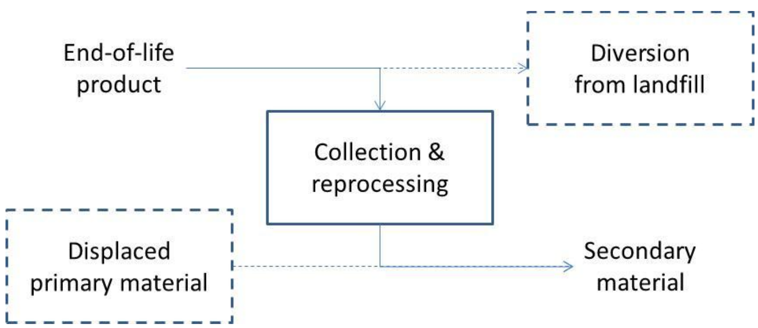

Figure 1: Analytical framework to assess greenhouse gas emissions reductions from polymer recycling.

The methodology used to quantify the energy and greenhouse gas emissions savings of polymer recycling is depicted in Figure 1. The gross savings of recycling are calculated as the sum of greenhouse gas emission savings from avoided landfill and avoided production of primary material. Polymer recycling has energy demand and greenhouse gas emissions of its own, which come from collection, transport to the reprocessors, and the reprocessing operations. In these guidelines only mechanical recycling is considered as reprocessing technology. The net greenhouse gas emission savings of polymer recycling are therefore the gross savings minus the additional emissions from collection, transport, and reprocessing.

The life-cycle energy demand and greenhouse gas emissions of the plastic product are calculated as

$$E_{total} = (1 - RC) \cdot \left(E_{prod} + E_{flog} + E_{disp}\right) + \frac{RC}{Y} \cdot \left(E_{coll} + E_{rlog} + E_{repro}\right) + E_{fab}.$$

The variables are defined as follows:

RC Recycled content

E_{prod} Energy demand or greenhouse gas emissions of cradle-to-polymer virgin plastic production

E_{flog} Energy demand or greenhouse gas emissions of forward logistics

E_{disp} Energy demand or greenhouse gas emissions of landfill of end-of-life product

E_{coll} Energy demand or greenhouse gas emissions of end-of-life product collection and transport to materials recovery facility

E_{rlog} Energy demand or greenhouse gas emissions of reverse logistics from materials recovery facility to reprocessor

E_{repro} Energy demand or greenhouse gas emissions of reprocessing

Y Reprocessing yield

E_{fab} Energy demand or greenhouse gas emissions of fabrication process

If the recycled content is zero ($RC = 0$), the above equation simplifies to

$$E_{total}(RC = 0) = E_{prod} + E_{fab} + E_{flog} + E_{disp}.$$

The energy and greenhouse gas savings from recycled content is simple the difference between the two:

$$E_{total}(RC = 0) - E_{total} = RC \cdot \left(E_{prod} + E_{flog} + E_{disp}\right) - \frac{RC}{Y} \cdot \left(E_{coll} + E_{rlog} + E_{repro}\right)$$

A frequently asked question is whether long transportation distances between the point of collection (typically a materials recovery facility) and the point of reprocessing might lead to a net increase in energy demand and greenhouse gas emissions. To answer this question we model reverse logistics E_{rlog} as a function of transportation distance. The only considered transportation mode is truck. The transportation calculations assume round trips.

Thermoformed Polyethylene Terephthalate (PET)

Table 2: Process inventory data for thermoformed PET.

Process	GHG emissions in kg CO_2E per kg polymer	Energy demand in MJ NCV per kg polymer	Data Source
Production (cradle-to-polymer)	2.70	73.00	[4]
Thermoforming	0.91	21.80	[4]
Forward logistics	0.15	2.10	[7]
Landfill	0.09	0.31	[1,7]
Cradle-to-grave (virgin PET benchmark)	3.85	97.21	
Collection	0.08	1.10	[7]
Transport to processor (500 km)	0.09	1.25	[7]
Reprocessing into polymer	0.96	14.91	[3]
Landfill of processing waste	0.02	0.08	[1]
Collection-to-recycled-polymer	1.15	17.34	

Table 3: Life-cycle greenhouse gas emissions per kg of thermoformed PET, in kg CO_2E, as a function of recycled content and transport distance to reprocessor. Virgin PET benchmark value is 3.85 kg CO_2E per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	2.11	2.54	2.98	3.41
1500 km	2.39	2.75	3.12	3.48
2500 km	2.67	2.96	3.26	3.55
3500 km	2.95	3.17	3.40	3.62
4500 km	3.23	3.38	3.54	3.69
5500 km	3.51	3.59	3.68	3.76
6500 km	3.79	3.80	3.82	3.83
7500 km	4.07	4.01	3.96	3.90

Table 4: Life-cycle greenhouse gas emissions of thermoformed PET, in percent reduction relative to all-virgin PET benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-45.2%	-33.9%	-22.6%	-11.3%
1500 km	-38.0%	-28.5%	-19.0%	-9.5%
2500 km	-30.7%	-23.0%	-15.3%	-7.7%
3500 km	-23.4%	-17.6%	-11.7%	-5.9%
4500 km	-16.1%	-12.1%	-8.1%	-4.0%
5500 km	-8.9%	-6.6%	-4.4%	-2.2%
6500 km	-1.6%	-1.2%	-0.8%	-0.4%
7500 km	5.7%	4.3%	2.8%	1.4%

Table 5: Life-cycle energy demand per kg of thermoformed PET, in MJ (net calorific value), as a function of recycled content and transport distance to reprocessor. Virgin PET benchmark value is 97.21 MJ NCV per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	40.06	54.35	68.64	82.92
1500 km	44.06	57.35	70.64	83.92
2500 km	48.06	60.35	72.64	84.92
3500 km	52.06	63.35	74.64	85.92
4500 km	56.06	66.35	76.64	86.92
5500 km	60.06	69.35	78.64	87.92
6500 km	64.06	72.35	80.64	88.92
7500 km	68.06	75.35	82.64	89.92

Table 6: Life-cycle energy demand of thermoformed PET, in percent reduction relative to all-virgin PET benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-58.8%	-44.1%	-29.4%	-14.7%
1500 km	-54.7%	-41.0%	-27.3%	-13.7%
2500 km	-50.6%	-37.9%	-25.3%	-12.6%
3500 km	-46.4%	-34.8%	-23.2%	-11.6%
4500 km	-42.3%	-31.7%	-21.2%	-10.6%
5500 km	-38.2%	-28.7%	-19.1%	-9.6%
6500 km	-34.1%	-25.6%	-17.1%	-8.5%
7500 km	-30.0%	-22.5%	-15.0%	-7.5%

Notes:

Typical product examples for thermoformed PET are food and non-food clamshells and blister packaging.

Maximum achievable greenhouse gas emission reductions are around 45 percent.

At a one-way distance of around 7,000 km (4,400 miles) between point of collection and point of reprocessing, PET recycling no longer generates greenhouse gas savings.

Injection Stretch Blow Molded Polyethylene Terephthalate (PET)

Table 7: Process inventory data for injection stretch blow molded (ISBM) PET.

Process	GHG emissions in kg CO_2E per kg polymer	Energy demand in MJ NCV per kg polymer	Data Source
Production (cradle-to-polymer)	2.70	73.00	[4]
Injection stretch blow molding	1.38	27.00	[4]
Forward logistics	0.15	2.10	[7]
Landfill	0.09	0.31	[1,7]
Cradle-to-grave (virgin PET benchmark)	4.32	102.41	
Collection	0.08	1.10	[7]
Transport to processor (500 km)	0.09	1.25	[7]
Reprocessing into polymer	0.96	14.91	[3]
Landfill of processing waste	0.02	0.08	[1]
Collection-to-recycled-polymer	1.15	17.34	

Table 8: Life-cycle greenhouse gas emissions per kg of ISBM PET, in kg CO_2E, as a function of recycled content and transport distance to reprocessor. Virgin PET benchmark value is 4.32 kg CO_2E per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	2.58	3.01	3.45	3.88
1500 km	2.86	3.22	3.59	3.95
2500 km	3.14	3.43	3.73	4.02
3500 km	3.42	3.64	3.87	4.09
4500 km	3.70	3.85	4.01	4.16
5500 km	3.98	4.06	4.15	4.23
6500 km	4.26	4.27	4.29	4.30
7500 km	4.54	4.48	4.43	4.37

Table 9: Life-cycle greenhouse gas emissions of ISBM PET, in percentage reduction relative to all-virgin PET benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-40.3%	-30.2%	-20.2%	-10.1%
1500 km	-33.8%	-25.4%	-16.9%	-8.5%
2500 km	-27.4%	-20.5%	-13.7%	-6.8%
3500 km	-20.9%	-15.7%	-10.4%	-5.2%
4500 km	-14.4%	-10.8%	-7.2%	-3.6%
5500 km	-7.9%	-5.9%	-4.0%	-2.0%
6500 km	-1.4%	-1.1%	-0.7%	-0.4%
7500 km	5.1%	3.8%	2.5%	1.3%

Table 10: Life-cycle energy demand per kg of ISBM PET, in MJ (net calorific value), as a function of recycled content and transportation distance to reprocessor. Virgin PET benchmark value is 102.41 MJ NCV per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	45.26	59.55	73.84	88.12
1500 km	49.26	62.55	75.84	89.12
2500 km	53.26	65.55	77.84	90.12
3500 km	57.26	68.55	79.84	91.12
4500 km	61.26	71.55	81.84	92.12
5500 km	65.26	74.55	83.84	93.12
6500 km	69.26	77.55	85.84	94.12
7500 km	73.26	80.55	87.84	95.12

Table 11: Life-cycle energy demand of ISBM PET, in percentage reduction relative to all-virgin PET benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-55.8%	-41.9%	-27.9%	-14.0%
1500 km	-51.9%	-38.9%	-25.9%	-13.0%
2500 km	-48.0%	-36.0%	-24.0%	-12.0%
3500 km	-44.1%	-33.1%	-22.0%	-11.0%
4500 km	-40.2%	-30.1%	-20.1%	-10.0%
5500 km	-36.3%	-27.2%	-18.1%	-9.1%
6500 km	-32.4%	-24.3%	-16.2%	-8.1%
7500 km	-28.5%	-21.3%	-14.2%	-7.1%

Notes:

Typical product examples for injection stretch blow molded PET are beverage bottles for soda, mineral water, sports drinks and other non-alcoholic beverages.

Maximum achievable greenhouse gas emission reductions are around 40 percent.

At a one-way distance of around 7,000 km between point of collection and point of reprocessing, PET recycling no longer generates greenhouse gas savings.

Blow Molded High Density Polyethylene (HDPE)

Table 12: Process inventory data for blow molded (BM) HDPE.

Process	GHG emissions in kg CO_2E per kg polymer	Energy demand in MJ NCV per kg polymer	Data Source
Production (cradle-to-polymer)	1.94	71.00	[4]
Blow molding	0.88	21.40	[4]
Forward logistics	0.15	2.10	[7]
Landfill	0.09	0.31	[1,7]
Cradle-to-grave (virgin HDPE benchmark)	3.06	94.81	
Collection	0.07	0.96	[7]
Transport to processor (500 km)	0.08	1.09	[7]
Reprocessing into polymer	0.39	6.76	[3]
Landfill of processing waste	0.01	0.02	[1]
Collection-to-recycled-polymer	0.54	8.83	

Table 13: Life-cycle greenhouse gas emissions per kg of BM HDPE, in kg CO_2E, as a function of recycled content and transport distance to reprocessor. Virgin HDPE benchmark value is 3.06 kg CO_2E per kg.

Distance to processor (by truck))	Recycled Content			
	100%	75%	50%	25%
500 km	1.49	1.88	2.27	2.67
1500 km	1.77	2.09	2.41	2.74
2500 km	2.05	2.30	2.55	2.81
3500 km	2.33	2.51	2.69	2.88
4500 km	2.61	2.72	2.83	2.95
5500 km	2.89	2.93	2.97	3.02
6500 km	3.17	3.14	3.11	3.09
7500 km	3.45	3.35	3.25	3.16

Table 14: Life-cycle greenhouse gas emissions of BM HDPE, in percentage reduction relative to all-virgin HDPE benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-51.4%	-38.6%	-25.7%	-12.9%
1500 km	-42.3%	-31.7%	-21.1%	-10.6%
2500 km	-33.1%	-24.8%	-16.6%	-8.3%
3500 km	-24.0%	-18.0%	-12.0%	-6.0%
4500 km	-14.8%	-11.1%	-7.4%	-3.7%
5500 km	-5.6%	-4.2%	-2.8%	-1.4%
6500 km	3.5%	2.6%	1.8%	0.9%
7500 km	12.7%	9.5%	6.3%	3.2%

Table 15: Life-cycle energy demand per kg of BM HDPE, in MJ (net calorific value), as a function of recycled content and transportation distance to reprocessor. Virgin HDPE benchmark value is 94.81 MJ NCV per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	31.20	47.11	63.01	78.91
1500 km	35.20	50.11	65.01	79.91
2500 km	39.20	53.11	67.01	80.91
3500 km	43.20	56.11	69.01	81.91
4500 km	47.20	59.11	71.01	82.91
5500 km	51.20	62.11	73.01	83.91
6500 km	55.20	65.11	75.01	84.91
7500 km	59.20	68.11	77.01	85.91

Table 16: Life-cycle energy demand of BM HDPE, in percentage reduction relative to all-virgin HDPE benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-67.1%	-50.3%	-33.5%	-16.8%
1500 km	-62.9%	-47.2%	-31.4%	-15.7%
2500 km	-58.6%	-44.0%	-29.3%	-14.7%
3500 km	-54.4%	-40.8%	-27.2%	-13.6%
4500 km	-50.2%	-37.7%	-25.1%	-12.6%
5500 km	-46.0%	-34.5%	-23.0%	-11.5%
6500 km	-41.8%	-31.3%	-20.9%	-10.4%
7500 km	-37.6%	-28.2%	-18.8%	-9.4%

Notes:

Typical product examples for blow molded HDPE are bottles for milk, detergent, household cleaning products, as well as bottles for personal hygiene and beauty products.

Maximum achievable greenhouse gas emission reductions are around 50 percent.

At a one-way distance of around 6000 km between point of collection and point of reprocessing HDPE recycling no longer generates greenhouse gas savings.

Injection Molded Polypropylene (PP)

Table 17: Process inventory data for injection molded (IM) PP.

Process	GHG emissions in kg CO_2E per kg polymer	Energy demand in MJ NCV per kg polymer	Data Source
Production (cradle-to-polymer)	1.98	70.00	[4]
Injection molding	1.27	25.30	[4]
Forward logistics	0.15	2.10	[7]
Landfill	0.09	0.31	[1,7]
Cradle-to-grave	3.49	97.71	
Collection	0.08	1.10	[7]
Transport to processor (500 km)	0.09	1.25	[7]
Reprocessing into polymer	0.96	14.91	[2,3]
Landfill of processing waste	0.02	0.08	[1]
Collection-to-recycled-polymer	1.15	17.34	

Table 18: Life-cycle greenhouse gas emissions per kg of IM PP, in kg CO_2E, as a function of recycled content and transportation distance to reprocessor. Virgin PP benchmark value is 3.49 kg CO_2E per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	2.47	2.72	2.98	3.24
1500 km	2.75	2.93	3.12	3.31
2500 km	3.03	3.14	3.26	3.38
3500 km	3.31	3.35	3.40	3.45
4500 km	3.59	3.56	3.54	3.52
5500 km	3.87	3.77	3.68	3.59
6500 km	4.15	3.98	3.82	3.66
7500 km	4.43	4.19	3.96	3.73

Table 19: Life-cycle greenhouse gas emissions of IM PP, in percentage reduction relative to all-virgin PP benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-29.3%	-22.0%	-14.7%	-7.3%
1500 km	-21.3%	-16.0%	-10.6%	-5.3%
2500 km	-13.3%	-10.0%	-6.6%	-3.3%
3500 km	-5.2%	-3.9%	-2.6%	-1.3%
4500 km	2.8%	2.1%	1.4%	0.7%
5500 km	10.8%	8.1%	5.4%	2.7%
6500 km	18.8%	14.1%	9.4%	4.7%
7500 km	26.8%	20.1%	13.4%	6.7%

Table 20: Life-cycle energy demand of IM PP, in MJ (net calorific value), as a function of recycled content and transportation distance to reprocessor. Virgin PP benchmark value is 97.71 MJ NCV per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	43.56	57.10	70.64	84.17
1500 km	47.56	60.10	72.64	85.17
2500 km	51.56	63.10	74.64	86.17
3500 km	55.56	66.10	76.64	87.17
4500 km	59.56	69.10	78.64	88.17
5500 km	63.56	72.10	80.64	89.17
6500 km	67.56	75.10	82.64	90.17
7500 km	71.56	78.10	84.64	91.17

Table 21: Life-cycle energy demand of IM PP, in percentage reduction relative to all-virgin PP benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-55.4%	-41.6%	-27.7%	-13.9%
1500 km	-51.3%	-38.5%	-25.7%	-12.8%
2500 km	-47.2%	-35.4%	-23.6%	-11.8%
3500 km	-43.1%	-32.4%	-21.6%	-10.8%
4500 km	-39.0%	-29.3%	-19.5%	-9.8%
5500 km	-35.0%	-26.2%	-17.5%	-8.7%
6500 km	-30.9%	-23.1%	-15.4%	-7.7%
7500 km	-26.8%	-20.1%	-13.4%	-6.7%

Notes:

A vast array of products is made from injection molded PP. The results above can also be used as a proxy for thermoformed PP.

Maximum achievable greenhouse gas emission reductions are around 30 percent.

At a one-way distance of around 4,000 km between point of collection and point of reprocessing PP recycling no longer generates greenhouse gas savings.

Injection Molded General Purpose Polystyrene (GPPS)

Table 22: Process inventory data for injection molded (IM) GPPS.

Process	GHG emissions in kg CO_2E per kg polymer	Energy demand in MJ NCV per kg polymer	Data Source
Production (cradle-to-polymer)	3.53	81.00	[4]
Injection molding	1.27	25.30	[4]
Forward logistics	0.15	2.10	[7]
Landfill	0.09	0.31	[1,7]
Cradle-to-grave	5.04	108.71	
Collection	0.07	0.99	[7]
Transport to processor (500 km)	0.08	1.13	[7]
Reprocessing into polymer (incl. processing waste landfill)	0.49	7.10	[1,2]
Collection-to-gate	0.64	9.22	

Table 23: Life-cycle greenhouse gas emissions per kg of IM GPPS, in kg CO_2E, as a function of recycled content and transportation distance to reprocessor. Virgin GPPS benchmark value is 5.04 kg CO_2E per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	1.97	2.73	3.50	4.27
1500 km	2.25	2.94	3.64	4.34
2500 km	2.53	3.15	3.78	4.41
3500 km	2.81	3.36	3.92	4.48
4500 km	3.09	3.57	4.06	4.55
5500 km	3.37	3.78	4.20	4.62
6500 km	3.65	3.99	4.34	4.69
7500 km	3.93	4.20	4.48	4.76

Table 24: Life-cycle greenhouse gas emissions of IM GPPS, in percentage reduction relative to all-virgin GPPS benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-61.0%	-45.7%	-30.5%	-15.2%
1500 km	-55.4%	-41.6%	-27.7%	-13.9%
2500 km	-49.9%	-37.4%	-24.9%	-12.5%
3500 km	-44.3%	-33.2%	-22.2%	-11.1%
4500 km	-38.8%	-29.1%	-19.4%	-9.7%
5500 km	-33.2%	-24.9%	-16.6%	-8.3%
6500 km	-27.6%	-20.7%	-13.8%	-6.9%
7500 km	-22.1%	-16.6%	-11.0%	-5.5%

Table 25: Life-cycle energy demand per kg of IM GPPS, in MJ (net calorific value), as a function of recycled content and transportation distance to reprocessor. Virgin GPPS benchmark value is 108.71 MJ NCV per kg.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	35.48	53.79	72.10	90.40
1500 km	39.48	56.79	74.10	91.40
2500 km	43.48	59.79	76.10	92.40
3500 km	47.48	62.79	78.10	93.40
4500 km	51.48	65.79	80.10	94.40
5500 km	55.48	68.79	82.10	95.40
6500 km	59.48	71.79	84.10	96.40
7500 km	63.48	74.79	86.10	97.40

Table 26: Life-cycle energy demand of IM GPPS, in percentage reduction relative to all-virgin GPPS benchmark, as a function of recycled content and transportation distance to reprocessor.

Distance to processor (by truck)	Recycled Content			
	100%	75%	50%	25%
500 km	-67.4%	-50.5%	-33.7%	-16.8%
1500 km	-63.7%	-47.8%	-31.8%	-15.9%
2500 km	-60.0%	-45.0%	-30.0%	-15.0%
3500 km	-56.3%	-42.2%	-28.2%	-14.1%
4500 km	-52.6%	-39.5%	-26.3%	-13.2%
5500 km	-49.0%	-36.7%	-24.5%	-12.2%
6500 km	-45.3%	-34.0%	-22.6%	-11.3%
7500 km	-41.6%	-31.2%	-20.8%	-10.4%

Notes:

Polystyrene is used for a diverse range of products such as plastic cutlery, CD cases, smoke detector housings, and license plate frames. The results above are based on injection molded GPPS, but can also be used as a proxy for thermoformed GPPS, such as yogurt cups.

Maximum achievable greenhouse gas emission reductions are around 60 percent.

Even at a one-way distance of 7,500 km between point of collection and point of reprocessing GPPS recycling still generates greenhouse gas savings.

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